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Optical Time-of-Flight Study of Lateral Exciton Transport in a Strained $Si_{1-x}Ge_x$/Si Multiple Quantum Well

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1. Introduction

Carrier transport in semiconductors of reduced-dimensions has received considerable interest from the perspective of fundamental physics and device applications. A number of approaches have been made and exercised to assess carrier transport in compound semiconductors. Recently, with the advent of SiGe heterostructure bipolar transistors, the significance of studying the transport properties of Si-based structures has been brought into the focus of attention. As opposed to compound semiconductors, electrical measurements have been widely used to study carrier transport in column-IV structures while optical techniques are very few. This is simply because many of optical methods rely on the detection of luminescence whereas the quantum efficiency in column-IV structures largely remains unnecessarily low [1].

In this study, we report the first attempt of optical time-of-flight (ToF) technique in measuring the lateral exciton diffusivity in a strained $Si_{1-x}Ge_x$/Si quantum well.

2. Experimental

The sample was a 50-period multiple QW (MQW) wth Ge content of 0.18 grown on an on-axis p-type Si(001). The well and barrier widths were 6.8 nm and 17 nm, respectively. The Si cap was 170 nm thick so that the MQW is totally covered by the penetration depth of excitation light source for luminescence measurement (514.5 nm line of an Ar^+ ion laser), which allows us to disregard the influence of perpendicular transport of excitons.

Exciton diffusivity was measured by a variant of optical ToF technique using metal mask with apertures that permit optical access [2,3]. A 50-μm thick stainless steel plate was etched and cleaned in a HF:HNO3 = 1:5 solution, and an array of circular apertures of various radii (20-120 μm) was created on a 800 μm grid by means of electric discharge machining (Matsushita, MG-ED72). The interior of as-machined apertures was found to be essentially free from burrs and of reasonable roundness under an optical microscope. The 800-μm center-to-center distance between two adjacent apertures was large enough to isolate individual aperture[4]. The aperture disc was finally blackened to reduce stray light due to Rayleigh scattering. The aperture disc was faced to the sample surface and mechanically clamped together with a cover glass on a copper cold finger of a vari-temp refrigerator.

Steady-state photoluminescence (PL) was collected using a cooled Ge detector (North Coast EO-817L) and an Ar^+ ion laser (488, 514.5nm) at a power density in the 0.1-1W/cm^2 range. The time-correlated single photon counting (TCSPC) was performed with a near-infrared-sensitized photomultiplier (Hamamatsu R5509-71). The excitation source was a cavity-dumped, mode-locked Ar^+ ion laser. Typical repetition rate was 800kHz and the system response time was better than 3ns.

3. Results and discussion

Exciton transport can be regarded as *diffusive* (*ballistic*) if the mean-free-path of excitons is smaller (larger) than the aperture diameter. In standard three-level scheme assuming exciton densities at level 1 (the initial state immediately after pumping) and level 2 (ground state), the following rate equations are appropriate [2],

$$\frac{\partial n_1}{\partial t} = D\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) n_1 - \frac{n_1}{\tau_R}$$
$$\frac{\partial n_2}{\partial t} = D\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) n_2 - \frac{n_2}{\tau_D} + \frac{n_1}{\tau_R} \qquad (1)$$

where D is the 2-dimensional diffusivity and τ_R and τ_D represent the intraband relaxation and radiative decay times, respectively. The solutions to Eq.(1) have a common factor describing the in-plane exciton diffusion

$$n(\mathbf{r},t) = \frac{n_0}{2Dt}\exp\left(-\frac{r^2}{4Dt}\right)\int_0^R r'\exp\left(-\frac{r'^2}{4Dt}\right) I_0\left(\frac{rr'}{2Dt}\right) dr' \qquad (2)$$

where I_0 is the modified Bessel function of zeroth order and n_0 is the initial carrier density.

The remaning part of the solutions to Eq.(1) contains the relaxation terms of identical form for both masked and unmasked cases. Thus, only *n* remains if we take the ratio between the two. The PL intensity at a given time is obtained simply by integrating *n* over the aperture area, which is to be compared with time-resolved experiment.

Shown in the upper panel of Fig.1 are the experimental PL decays of a masked sample with circular hole diameter of 78 μm and an unmasked one. As expected, the trace for the masked sample decays faster and provides lower photon counts than the unmasked one at all times as a result of

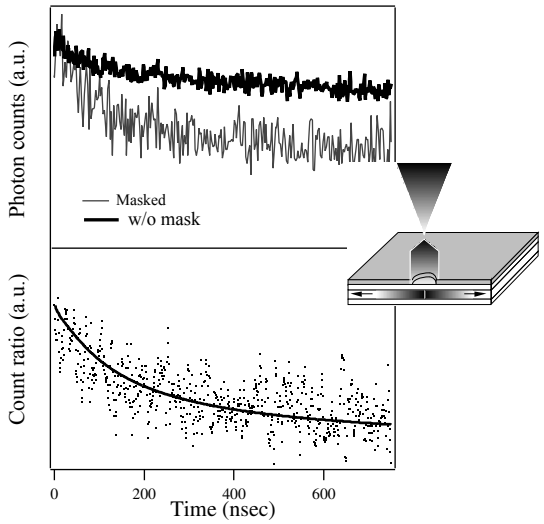

FIG.1 The upper panel shows the experimental decays of masked (aperture diamter of 78 μm) and unmasked samples taken at 40 K. The dots in the lower panel represent the ratio (masked / unmasked) and the solid line is the best fit using D = 29cm^2/s. Inset shows the excitation / collection geometry.

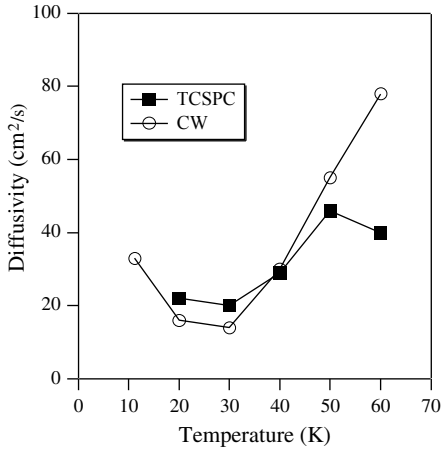

Fig.2, Temperature dependence of exciton diffusivity in strained $Si_{1-x}Ge_x$/Si MQW as deduced from cw (open circles) and time-resolved (filled squares) measurements. At higher temperatures (T$>$30K), the exciton diffusivity is proportional to temperature.

exciton diffusion out of the circular aperture [5].

The lower panel in Fig.1 shows the ratio of decays between the masked and unmasked samples as a function of time. The solid line is a best fit using Eq.(2) with D = 29cm^2/s at 40 K.

Shown in Fig.2 by filled squares is the temperature dependence of diffusivities. A 78-μm aperture was used. Also plotted by open circles are the diffusivities obtained by cw measurement in which the PL intensity as a function of temperature was fitted to the time-integrated solution of Eq.(1). As the diffusivity obtained by cw study is scalable, the D value at 40 K was assumed to be the same as that of the time-resolved measurement. Both curves are seen to closely match each other except at 60 K.

At higher temperature (T$>$30K), the diffusivity is nearly proportional to the temperature reflecting the thermal activation or the kinetic energy of exciton. In contrast, at temperatures lower than 30 K the diffusivity tends to increase with decreasing temperature. Such anomaly has also been observed in lateral transport of excitons in AlGaAs/GaAs QWs [2]. Athermal, nonequilibrium phonons having excess energies provided by the initial laser pumping are expected to be responsible for this.

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